PopCAD: Toward Paper-Based Fabrication Tools for Education

Ben Leduc-Mills
Dept. of Computer Science
University of Colorado, Boulder
Boulder, CO USA
303-735-6042
ben@benatwork.cc

Michael Eisenberg
Dept. of Computer Science
University of Colorado, Boulder
Boulder, CO USA
303-492-8091
duck@cs.colorado.edu

ABSTRACT
This paper describes a working prototype device, PopCAD, for straightforward, tangible 3-dimensional input and design. PopCAD is a paper-based pop-up computational artifact that can be carried about easily and unfolded into its “working” instrumental form. When unfolded, PopCAD allows the user to switch on LED lights in a 3D spatial array; the positions of these lights are sent to a desktop computer for display and manipulation in real time. The intent of the device is thus twofold: first, to provide an experience of embodied construction for students and 3D designers, and second, to illustrate the power and potential of designing working sophisticated instruments based on an inexpensive, flexible paper substrate. We describe PopCAD’s architecture, its origins in earlier projects, and the learning potential inherent in such a device. We also show a variety of project ideas that the device can implement and we discuss what the device implies for the future of paper-based tangible instrumentation.

Categories and Subject Descriptors
H.5.2 [Human Factors]: User interfaces – input devices and strategies.

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Design, Human Factors.

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PopCAD, SnapCAD, embodied fabrication, paper-based instrumentation.

1. A PAPER-BASED FABRICATION TOOL
This paper describes a novel prototype for a "computer peripheral"–novel in both purpose and material design. The device, PopCAD, is–in physical form–created on a paper substrate, and similar in operation to a pop-up card: it can be carried flat and unfolded into an open, working form. When unfolded, the device can be used as a computer peripheral, permitting the user to specify locations directly, "by hand", in 3D space for the purpose of solid modeling and design, especially tuned for output to a 3D printer. The intent of PopCAD is thus to demonstrate two fundamental (and complementary) ideas: first, a method for creating 3D models via "embodied" means, bypassing the limitations of a two-dimensional screen as an input device; and second, to achieve this purpose in lightweight, affordable, classroom-friendly, and flexible materials. Figure 1a shows PopCAD in its "opened" form, while Figures 1b and 1c show the device in the course of being folded flat.

The remainder of this paper is devoted to a fuller discussion and exploration of the PopCAD project. In this introductory section, we begin by motivating the project as a method of creating 3D objects through direct, hand-based means (a style of creation that we refer to as embodied construction). We also outline the history of PopCAD's design, showing how it emerged from an earlier project (called UCube) which illustrated the principles of embodied construction, but which did so by using a bulkier and more expensive material design.

The second, "technical" section provides a description of PopCAD's current architecture and software. The third section then builds upon this description, as we present a variety of sample projects that PopCAD is capable of supporting; this section also addresses some limitations of the system. The fourth section discusses some of the larger issues raised by PopCAD in the areas of embodied cognition, potential learning outcomes, 3D design, and paper-based instrumentation; this section also includes an overview of related work in these areas. We conclude with a brief sketch of ongoing and future work on PopCAD in our lab.

1.1 Seeking Natural, Embodied 3D Modeling for Fabrication
Three-dimensional design–the creation of 3D objects for representation in a computer–represents a thorny challenge for interface design. On the one hand, this sort of design is undeniably important, and likely to become more so: the world is now awash in 3D graphics images, and increasingly these images are presented not only on flat screens, but also on specialized 3D display devices. Perhaps most excitingly, the rapid growth of 3D printing and fabrication allows users to realize their spatial ideas in tangible form. In short, then, to be an expressive creator of graphics or physical objects now implies a familiarity with 3D modeling and design.
Despite the excitement, currency, and importance of the field, however, there is no denying that three-dimensional design is hard. Even the best, most well-designed three-dimensional design and construction software such as Rhino (Rhino, n.d.) or Sketchup (Google, n.d.) requires users to translate their spatial ideas into forms rendered on a flat two-dimensional screen. The concepts and terminology implied by this translation process—notions such as “virtual camera positions”, “extrusion”, “guide-lines”, and many others—present a huge cognitive hurdle for novice learners. The essence of the problem is simply that a flat screen is not a perspicuous medium with which to create or manipulate 3D forms; the creation process does not take advantage of our (human, real-world) spatial intuitions and bodily experience.

The idea behind the PopCAD system is to provide a 3D space—a limited volume—in which to specify 3D points by hand, without the need for a 2D screen. The view in Figure 1a, which shows the "opened-up" system, suggests the basic principle: here, there are nine paper towers spaced in a regular 3-by-3 array. On each tower, there are three (again, evenly spaced) locations with embedded LED lights that the user can switch on or off. Thus, there are a total of 27 (3x3x3) locations that can be specified by the state of a PopCAD light. In a sense, then, the open PopCAD system can be regarded as a “display” of 27 points (with integer coordinates) in a region of 3-space.

The entire PopCAD device is connected to a desktop computer, and by turning on a particular set of lights, the user can now communicate that set of locations (or points in 3-space) to the computer. Once this is accomplished, the computer can (among other possibilities) create a solid form specified in some fashion by these chosen points. Just to take a concrete example: if the user switches on the eight lights at the eight extreme “corner” locations of the PopCAD device, these points could be communicated to the desktop computer, and used to designate the vertices of a cube(1). We will return to a much more extended discussion of PopCAD's use later in the third section of this paper.

1.2 Steps in the Development of PopCAD

PopCAD, as outlined thus far, is a paper-based input device that can be used to specify a (limited) number of points in a region of 3-space. It is worthwhile, before discussing the system further, to indicate the origins of the system in our own previous system development.

Figure 1: (a, top) The PopCAD system in its opened, unfolded form. In this form, the system presents a set of nine paper "towers" on which LED lights can be affixed; in the photograph, seven of the available locations in fact have their LED lights switched to the "on" state. (b, center) The PopCAD system, in an intermediate state, now being "folded down" into its flat form. (c, bottom) The PopCAD system, now folded flat.

Figure 2: (a, top) The SnapCAD system, a predecessor to PopCAD. The device shown here consists of a 7-by-7 array of holes into which “towers” can be placed. Here, 4 towers (of a maximal possible 49) have been placed in the device, and LED lights have been attached to locations on the towers to specify locations in space. (b, bottom) As eight cube corners are specified by lights on the SnapCAD towers, the corresponding solid is shown on the screen of the computer attached to the device.
PopCAD may be viewed (or, at least, this is how we view it) as the latest successor to an earlier set of 3D input devices constructed in our lab. The most recent previous effort, called SnapCAD (a photo is shown in Figure 2), is a large box-shaped input device in which an array of holes can be seen in the top surface. Within each hole, a plastic “tower” may be inserted; each tower has a set of locations, spaced vertically, onto which an LED light may be affixed, or “snapped” on magnetically. The entire set of specified points may then be communicated to a connected desktop computer, as shown in Figure 2b. It should be mentioned that the Figure 2 device has a 7-by-7 array of holes, and each tower has 7 evenly-spaced vertical locations; thus, the Figure 2 device is capable of representing 343 (7x7x7) distinct locations in 3-space.

The historical connection between the earlier devices and PopCAD should be apparent: both devices are predicated on the idea of specifying volumetric points easily, “by hand”, within a spatial array, and communicating those points to a computer for further display and processing. The earlier device is clearly, by some measures, superior to the newer one: in particular, by providing a much larger array of available points, it is a far more powerful 3D input device. On the other hand, because of the SnapCAD’s material design, it is a large, bulky, expensive, and (in practice) stationary device. The purpose of our first PopCAD prototype is to demonstrate that it is possible to retain the strengths of the SnapCAD as a means of embodied construction, and to combine those strengths with the remarkable advantages of paper as a material substrate for design. (Not coincidentally, it should be noted that a paper-based device could prove far more realistic for informal, classroom use.) In time, we plan to develop more powerful versions of PopCAD, to bring it closer to the expressive range of the SnapCad of Figure 2; we’ll return to this issue toward the end of this paper.

2. POPCAD: DESIGN AND SAMPLE SCENARIO

The PopCAD book is approximately 13x13 inches in (top) surface dimension when closed, as in Figure 1c; the paper towers displayed in Figure 1a are about 9 inches in height, 1.5 inches wide and 1 inch deep. As noted, the opened book, with its nine towers, represents a suspended 3-dimensional grid of points in space, 3x3x3 in size. The 27 points in the grid are evenly spaced 3 inches apart on each axis; the foldable construction paper towers contain the electronics, LEDs, and necessary paper engineering elements (e.g. paper support struts). Each of these towers follows the schematic illustrated in Figure 3.

The front face of each tower displays 3 LilyPad Arduino LED lights, which are attached to the paper via a circuit made of adhesive copper tape. On the left face are 3 pieces of copper tape, aligned vertically with each LED. These strips are used as capacitive touch sensors and act as the switch to turn on and off the LEDs. In order for copper tape to behave in this manner, we implement a common method that sets a timer on the pin that the copper tape is connected to. We turn on the internal pull-up resistor on that pin and then connect the resistor to ground, effectively bringing the pin to a ‘LOW’ state. We can then time how long it takes to get to return to a ‘HIGH’ state. If the resistor takes more time than normal (above a certain threshold), we can surmise that a capacitive object has made contact with the copper tape and toggle the associated LED on or off. The three LEDs, three capacitive switches, and a ground connection are wired to headers underneath the surface of the paper, which in turn route the signal to appropriate pins on an Arduino Pro Mega microcontroller.

The microcontroller is also continuously polling the switches and sending the current state of each LED (either a 0 or 1) out over the serial port. This information in turn is sent to a desktop software program (through a standard USB cable) that intercepts the string of numbers and visualizes them as points in 3-space on the screen—in real time. The active LEDs are visualized as larger grey dots set within a ‘ghosted’ grid of all the potential points. A simple graphical user interface allows users to interpret the set of active points in several different ways: by taking the convex hull represented by the points (see, for instance, Figure 2), by connecting in sequence the points in the order in which they are activated creating a path through space, and by taking the minimal spanning tree of the active set of points. At any point in the modeling process the current shape can be exported to a stereolithography (.STL) file—the preferred format for 3D printing. This, as noted earlier, is one of the primary motivations for developing a system such as PopCAD—namely, as a straightforward tangible design interface for creating printed-out physical objects.

Figure 3. A schematic of a paper tower (shown in its opened configuration, as in Figure 1). The elements of this schematic are elaborated in the accompanying text.
Beyond the features of the software already mentioned, there is also an “edit” mode whereby the current shape is “frozen” by not reading live input from the book and instead points can be perturbed off the integer lattice by clicking and dragging them with the mouse. These edited points can be shared between the convex hull, knot/path, and minimal spanning tree modes. Together, these modes represent a surprisingly large number of potential 3D-printable shapes—many more than one might assume given a 3x3x3 grid.

It is worth mentioning, at this juncture, several of the design challenges in creating a usable paper instrument of the sort exemplified by PopCAD. As it happens, to design a foldable paper grid of nine columns, many designs were considered and discarded for various reasons: the columns were too close together to reach between them, the design did not allow for equidistant points across all axes, the paper structure was too flimsy, etc. Interestingly, the laser cutter in our lab proved to be an excellent prototyping tool for this kind of paper craft design. The laser cutter allows rapid iterations from digital files with otherwise uniformly consistent results effectively allowing us to isolate variables in the design we wished to change. The design we settled on uses only one center crease to “power” the pop-up motion of all nine towers. This is possible through a set of paper “struts” that connect the center row of towers to the two other towers in its column (in front and behind). In order to fit the struts and the circuitry, we had to carve out “windows” in each tower to provide places for the struts to attach. By designing struts with enough pull, and securing only the external edges of the outside towers to the paper (so that the columns can lay flat when the book is folded) we found a solution that was both sturdy and had a very pleasing pop-up effect.

2.1 A Typical PopCAD Scenario

In the following section, we will present a variety of sample projects that can be undertaken with PopCAD. Before proceeding, however, it is worth “putting together” the elements that we have shown in a typical scenario. The user begins by opening up the PopCAD book, and connecting it to a desktop computer (onto which the PopCAD software has been downloaded). The user then selects, among the 27 available points, the vertices of a shape that she wishes to create; checks that shape against its appearance on the computer screen (as in the view shown in Figure 5); and, if satisfied, sends that shape on to some other program, or (alternatively) sends the shape to be output by a 3D printing device. There are, of course, important limitations to this scenario—and we will touch upon these in the ensuing discussion. Nonetheless, it is the overall simplicity of the scenario that is worth noting here, and that originally inspired the design of PopCAD (and its UCube predecessor.

The user need not construct a shape on a two-dimensional screen, nor be deeply familiar with the terminology and operations of modeling software. Instead, the creation of a desired shape takes place by moving one’s hands in space. No overly precise movements are necessary—a point on the PopCAD is either on or off, and can easily be toggled on and off at any point in the modeling process—a very different scenario than using most 3D modeling software. As another guiding heuristic for our design, it should be noted that the PopCAD software is intentionally minimal. Although there are still some additions to the software that we expect to see implemented in further iterations (see the final section), our aim is not to produce another sophisticated software modeling program. Instead, the software is meant to aid the user in clarifying their physical actions with the PopCAD towers and switches.
3. POPCAD PROJECTS: A SAMPLER

The previous section described the architecture and implementation of the PopCAD. In this section, we outline a variety of 3D design projects that can be undertaken with the system. Unquestionably, the reader will have noted that the current (initial) PopCAD prototype—containing as it does only a 3x3x3 grid of spatial locations—is highly limited in scope; we will address this issue, and other limitations, in the final section of this paper. Still, even the current tiny PopCAD reveals surprising capabilities as a modeling device.

3.1 Convex Hull (Polyhedral Forms)

The most straightforward type of 3D modeling done with PopCAD is to create polyhedral forms, such as the one displayed in Figure 4(a). The basic scenario here is that the user selects a set of locations in space by switching on lights at those locations; these lights can be interpreted as the outer (hull) vertices of a convex shape. The PopCAD software can then display and print out the convex hull of the selected input points.

3.2 Points as Blocks (Nonconvex Polyhedra)

While a “standard” PopCAD project interprets the locations of lights as vertices of a polyhedron, the device allows for myriad different semantics for spatial locations. For example, we might wish to interpret the location of a light as signifying the presence, not of a point, but of a cube in space, centered at the given location and with an edge-length of one "tower-interval unit". By selecting (say) three successive light locations along the length of one tower, then, one could specify a rectangular prism; likewise, by selecting three point locations in an “L” form, one could specify the non-convex polyhedral form seen at the far right of Figure 4b. For those readers interested in recreational mathematics, the seven block pieces in Figure 4b will be recognizable as the component pieces of the popular “Soma” puzzle; these pieces can be arranged together to form a cube.

3.3 Paths: Creating Linear Forms and Knots

In the examples of the previous paragraphs, we have not made use of the fact that PopCAD samples selected points in real time: thus, when a user adds or subtracts a point in space, that change is registered immediately in the desktop software. What means this is that the user can exploit not only the overall set of selected points, but can also make use of the order in which those points are selected. A sequence of selected points need not represent only vertices of a solid; it can also represent a path over time in 3D space.

Figure 4c shows a sample project based on this idea. Here, the PopCAD software has been employed to read points as successive positions of a path in 3-space. The resulting path has been printed out on a 3D printer.

3.4 Point Clouds: Minimal Spanning Trees

Instead of interpreting points as vertices of a solid (as in the convex hull examples) or as the successive stations of a temporal path (as in the “path” example above), we could in fact simply treat our set of points as just what they are—namely, a set of points. Starting with this interpretation, we might produce a form such as a minimal spanning tree of the set of points (a set of edges of minimal total length connecting all the points). Figure 5 shows an example of a form created this way: here, the PopCAD software has computed a minimal spanning tree from a set of nine selected points, and the tree is then printed out in solid form as one of the shapes shown in Figure 5.

3.5 Limitations of PopCAD

It should be apparent from the examples shown above that PopCAD, as an input device, suggests a variety of 3D design projects; at the same time, the astute reader will have no doubt noticed important limitations in the device. To take the most obvious: because it offers only 27 spatial points to the user, the shapes that PopCAD can create are relatively small in size and limited in complexity. The earlier SnapCAD device had 343 available points, giving rise to a much larger available design space. Beyond this obvious point, because PopCAD makes use of points on an integer lattice, it is not easily suited to shapes that require either fine detail (e.g., curved forms, natural forms such as trees) or large numbers or extreme ranges of constituent points (e.g., a tall building). Indeed, the lattice arrangement of points means that there are many well-known “classic” shapes (such as a regular dodecahedron) which could not be modeled—or at least not naturally or easily modeled—using PopCAD, since their vertices cannot all be located on such a lattice.

We intend to build a larger “PopCAD 2.0” with more available points; this will significantly extend its expressive range, but of course this does not fully resolve the “integer lattice” limitations mentioned above. Conceivably, some of these limitations could be finessed by adding additional functionality to the software (as with the “edit” mode); but our own feeling is that, rather than trying to move the device in “disembodied” directions of this sort, it would be more reasonable to think of PopCAD as one very simple device among a suite of 3D input tools and techniques, each with their own strengths and limitations. Ideally, a 3D designer might thus be equipped with several mutually compatible devices (including PopCAD) to tackle a variety of modeling tasks.
4. REFLECTIONS
Having described both the architecture and expressive range of PopCAD, it is now time in this section to step back and reflect on the overall goals of the device, and to situate this work within the larger landscape of both 3D modeling and tangible design. The overall purpose of the device is, first, to bring an “embodied” approach to the task of 3D modeling and construction—to integrate the power and capabilities of computational modeling and fabrication with the affordances of hand movements in space. The second purpose is to illustrate the power of paper-based electronics as a means of creating tangible artifacts. We begin our discussion with the first of these goals.

4.1 Toward Embodied 3D Design
In the context of “natural 3D modeling”, PopCAD can in fact be placed within several traditions of work. On the one hand, there are a number of research projects that have experimented with hand or gesture-based means of creating 3D input for computers: the iSphere project (Lee et al., 2006) was a provocative example along these lines, using a custom-built dodecahedral input device to read user gestures, while Sreedharan et al. (Sreedharan et al., 2007) describe a technique for 3D input using a Wii controller. Recent projects such as (Benko et al., 2012; Folker and Ishii, 2012; Jota and Benko, 2009; Pruch, 2010) are similarly geared toward using physical movements or objects as the basis of 3D design, and typically these projects also share with PopCAD an abiding interest in physical fabrication (e.g., using a 3D printer) as an important aspect of 3D design more generally.

Another line of work important to our design is the more theoretical field of “embodied cognition”, in which cognitive tasks are interpreted not solely in abstract, computational terms, but in the context of an active body (usually, but not exclusively, a human body) solving problems and drawing analogies from the physical world. (See Clark, 1997 for a good popular introduction to the philosophy behind this approach.) PopCAD in particular draws on that aspect of embodied cognition theory that relates gestural and physical intuition to mathematical or spatial understanding (Goldin-Meadow, 2003; Lakoff and Nunez, 2000; Arzarello and Edwards, 2005). Recent educational work by Abrahamson and his group (Abrahamson, 2011) has focused on the design implications of embodied cognition in mathematics, creating physical devices to support embodied intuitions for mathematical concepts. Abrahamson's work, in turn, can be linked to a tradition of creating tangible artifacts for mathematical education—for example, Resnick's “digital manipulatives” (Resnick et al., 1998).

While PopCAD draws upon ideas and influences from these bodies of work, it also introduces potentially novel themes into both traditions. To begin with the cognitive/educational side first: it is clear that PopCAD has a pedagogical dimension, and can be viewed as a device to both introduce, scaffold, and practice important skills in spatial reasoning. There is no shortage of material supporting the potential learning aspects of tangible play and exploration: constructivist theory has long believed in a link between active, physically-engaged problem solving and learning (Piaget, 1953). Later studies have shown that physical movement can aid in recall and categorization tasks involving spatial imagery and perspective (Reiser, 1994). Additional research on tangible user interfaces (TUIs) and children’s learning have suggested that a multi-modal approach (such as the interplay between the PopCAD book and the software running on a computer) is often the most effective at producing positive learning results (Price and Carey, 2013; Horn et al., 2011) given a diverse range of learners and tasks. Our earlier pilot tests (Leduc-Mills et al., 2012) with middle school children support this interpretation of the device: one might imagine employing PopCAD in a classroom to introduce concepts of 3D coordinates; the device could be treated as a source of challenging puzzles (model a shape from a given 3D-printed object); or it could be used a foundation for laboratory experiments in spatial cognition. Nonetheless, despite all these possibilities, our goal in creating the device is not solely pedagogical—or to put the matter differently, we view the device as supporting educational goals in the context of creative design. PopCAD—at least in its future, larger, implementations—is not imagined just a *teaching* or *skill-training* tool, but rather a tool to support expressive (and potentially practical) activity. By the same token, the goal of PopCAD (unlike some projects in the “3D design” tradition) is not simply to make 3D creation easier or more natural. Often, there seems to be an implicit equation in projects of this sort between “ease of use” and “informality”—employing, for example, simple or informal gestures as means of input for spatial forms. Our device, as we have shown, is both *embodied* in its approach to 3D input, but *formal* in its incorporation of 3D coordinate geometry into the design process. We believe that embodied cognition can, in fact, be integrated into the larger intellectual project of developing spatial expertise and geometric reasoning.

4.2 Paper-Based Instrumentation
The second major purpose of the PopCAD project is to rethink our earlier SnapCAD design with a novel (and potentially more expressive) material—notably, paper—as the foundation for construction. In this context, PopCAD is an illustration of a still embryonic but growing design tradition exemplified by the brilliant work of Qi and Buechley (Qi and Buechley, 2012). For the most part, it is fair to characterize that work as primarily “artistic” in intent (creating, e.g., beautiful computationally-augmented pop-up forms); whereas PopCAD, in contrast, is an illustration of electronically-enhanced paper as a basis for instrumentation design.

Several advantages of paper for a device like PopCAD (in contrast to the earlier SnapCAD) are apparent: the newer device is light, portable, and inexpensive (perhaps $75 in contrast to over $1K for the SnapCAD). Unlike SnapCAD (which was conceived as a rather imposing desktop device), PopCAD is the sort of instrument that one might take back and forth between work and home. It is light enough to be carried about easily by (say) a middle school student, and potentially sturdy enough for (still somewhat careful) classroom use, as shown by our initial user pilot tests. Indeed, because PopCAD lends itself to a wide variety of settings, it has occurred to us that it would be worthwhile to implement a version of the PopCAD software on a portable device (such as a tablet); this is one of our goals for continued development of the system. This is an interesting illustration of how the redesign of the material composition of an input device can provide the impetus for software redesign as well.

Finally, there is one last intellectual tradition to mention in the context of this project. Our goal in creating PopCAD is not to build a “stand-alone” device, but rather to create an object whose purpose is to work *in concert* with other devices, in an enabling role. PopCAD is an input device for a computer, but it also can be seen as a simple, paper-based artifact for 3D modeling and fabrication (and thus as an artifact that makes a 3D printer more useful in the process). More broadly—as noted earlier—we might envision the ultimate development of 3D design studios in which...
a variety of devices (gestural input devices, physical modeling kits, and PopCAD-like devices) combine and merge to facilitate a wide range of graphical and physical expression. In this respect, our design has been strongly influenced by the ideas of W. Brian Arthur (Arthur, 2009), who urges an “ecological” view of technological development, in which various artifacts and techniques play important roles by virtue of their relations (often though not always symbiotic) with still other artifacts and techniques. PopCAD is intended as just such an ecological addition to the technological landscape—a device that could work in concert with 3D modeling software and 3D fabrication tools, and that could eventually be combined and integrated with a suite of complementary input devices.

Figure 6. A collection of printed-out 3D forms made by students in creative "free-form" play sessions with the PopCAD and SnapCAD systems.

5. ONGOING AND FUTURE WORK

PopCAD is still in some ways a work-in-progress. We have recently completed initial pilot tests of the system with middle school age students, focusing on usability and understandability of the device. While these tests will be the focus of a subsequent paper and are beyond the scope of this (more design-oriented) paper, it is clear from these tests (and our pilot tests of PopCAD’s predecessors) that the notion of embodied design is realistic and that children can in fact make creative and productive use of the system. (Leduc-Mills, 2014; Leduc-Mills and Eisenberg, 2011; Leduc-Mills et al., 2012) Just to mention one interesting preliminary result from the pilot tests: to our surprise, some students made use of the PopCAD device to create "2D" printed-out forms by employing only one available plane of the spatial array; the students were thus able to print out (e.g.) some common letter shapes. It simply hadn't occurred to us beforehand that this might be a "natural" use of the system. Figure 6 shows a collection of printed out forms created by students in the pilot-tests making use of both PopCAD and the earlier SnapCAD system: again, the range of creations (and the fact that they were made after only relative brief exploration of the device) suggests that the goal of embodied fabrication for students is an achievable one.

Our near-term goal is to create a larger, more expressive version of PopCAD. There are naturally many technical improvements and extensions to be made in both the hardware and software of the device. Conceivably we may wish to extend the range of colors available for PopCAD LED elements; or we may wish to design novel types of paper-based additions to extend the "core" PopCAD design. We also wish to explore the potential of integrating the PopCAD software with more traditional (and powerful) 3D modeling applications, to allow the device (along with the SnapCAD) to be used as both an introductory (or “training”) tool for 3D novices, and as a practical input tool for more expert users. In the longer term, we wish to think of PopCAD as one of a larger suite of tools and artifacts that better enable both children and adults to express themselves through physical construction and design, and to do so through the use of expressive, flexible materials. Bringing computation, and paper-based design, into tangible, sculptural, and material construction will clearly be central in the technological evolution of craft activities; PopCAD is a promising step toward making these creative and playful crafts more accessible and enjoyable for a wide audience.

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7. REFERENCES


